Star formation in galaxies hosting Active Galactic Nuclei up to $z \sim 1$

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1.1 Introduction

This contribution aims to address the fundamental question, effectively highlighting the overall theme of the workshop, as to what processes are important for eventually suppressing the growth of supermassive black holes (SMBHs) and how is this related to the evolution of star formation from $z \sim 1$ to the present. As illustrated in Figure 1.1, a global decline in mass accretion onto SMBHs and star formation rate density over the last 8 Gyrs [1, 2, 3] is evident and may be driven by a mechanism such as feedback from AGN affecting the gas content of their hosts [4, 5, 6]. Such coupling may not only explain the local SMBH-bulge relations (see [7] for an overview) but rectify the inconsistency between the observed distribution of high-mass galaxies and that predicted by semi-analytic models [8].

Intriguingly, there is observational evidence for AGNs influencing their larger-scale environments that may lend support for the aforementioned feedback models. For example, radio jets are capable of impacting their intracluster medium [9] that may then inturn regulate further cluster cooling and inhibit star formation in the AGN host galaxy itself [10]. Even at low power, radio-emitting outflows are capable of redistributing line-emitting gas in galactic nuclei [11]. Furthermore, QSO-driven winds are a common phenomenon having kinetic energies quite capable of expelling gas especially from the nuclear region. Although, it has not been demonstrated that AGNs or the more luminous QSOs are responsible for quenching star formation on galactic scales.

Recent studies are providing evidence that may indicate an impact of AGNs upon their host galaxies. For example, X-ray selected surveys [12, 13, 14, 15] that utilize the obscured AGN population to enable a fairly clean view of the host galaxy demonstrate that many have rest-frame optical colors placing them in a region of the color-magnitude diagram usually populated with transitional galaxies (i.e., 'green valley'; $U-V \sim 0.7$; See Figure 1.2 left panel). This suggests that AGN feedback may contribute to the migration of galaxies from the 'blue cloud' to the 'red sequence'. We note that the subject of the location of AGN hosts on the color-magnitude diagram may present an incomplete picture that will be addressed below [16].

To further explore the role of SMBHs in galaxy evolution, we aim to determine whether AGNs are directly regulating the current rate of star formation that may then depend on the accretion rate of the black hole itself. To do so, it is imperative to construct large samples of galaxies ($>$

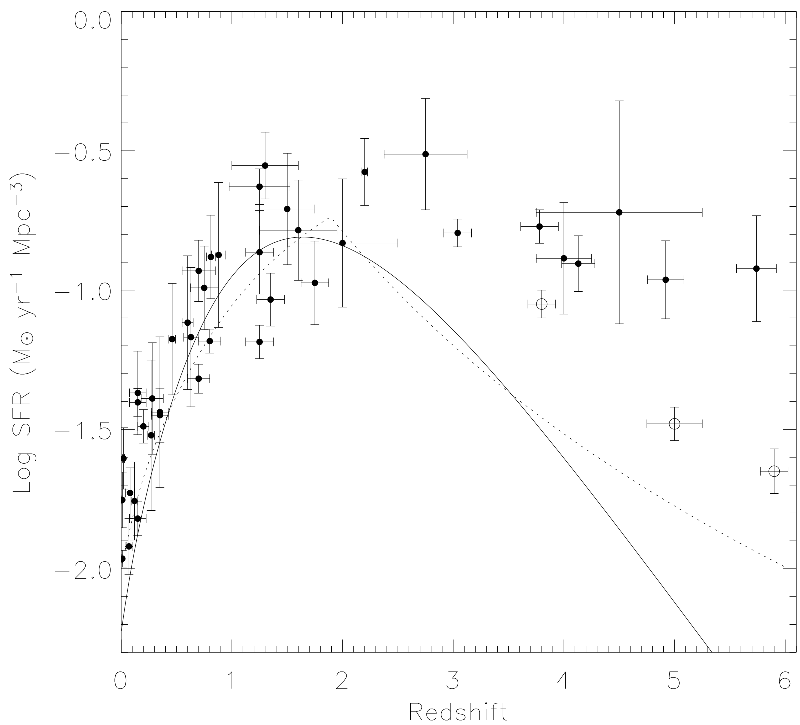

Fig. 1.1. Global evolution of star formation rate density (data points) and mass accretion rate density onto SMBHs scaled up by a factor of 5000 for comparison (curves; See [3] for details).

10k) and compare ongoing star formation rates of galaxies hosting AGN to those of the underlying galaxy population. The short duty cycles of accretion onto SMBHs [17] dictate the need for samples of such size. A spectroscopic nature for the sample will further allow the disentanglement of environmental factors that are known to influence star formation (see [18]). In addition, a multi-wavelength approach is a necessity in order to

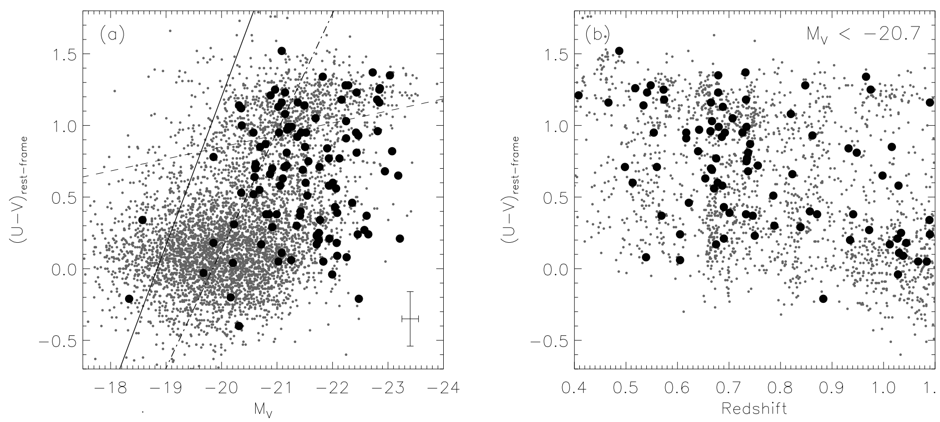

Fig. 1.2. Host galaxy colors of AGNs in the Extended *Chandra* Deep Field - South survey: *left* Rest-frame color versus absolute magnitude, *right* Rest-frame color versus redshift. Galaxies with photometric redshifts from COMBO-17 [29] are shown in grey while those hosting X-ray selected AGN are marked by the larger black circles. See [13] for further details.

characterize the intrinsic properties of the galaxy population (e.g., stellar mass).

The advent of such surveys starting with the Sloan Digital Sky Survey (SDSS) are enabling investigations of the relationship between galaxy and SMBH growth. Based on the enormity of the SDSS database, it has been clearly shown that galaxies hosting obscured AGN have young stellar populations, equivalent to late-type galaxies [19, 20] thus clearly establishing a direct relationship between SMBH accretion and star formation. On the contrary, differences between the stellar populations of AGN hosts and galaxies lacking AGN signatures in the SDSS have been reported [21], similar to the results based on X-ray selected AGNs, and are attributed to the suppression of star formation but may be due to selection (e.g., luminosity versus stellar mass).

Recently, large-scale spectroscopic redshift surveys (e.g., DEEP2, COSMOS) have targeted the galaxy population out to higher redshifts ($z \sim 1$) thus beginning to probe the peak of star formation and AGN activity. A full multi-wavelength (UV-to-IR) approach is realized to effectively characterize the galaxy population and its evolution. Equally important, the identification of galaxies at $z > 0.3$ that host obscured AGN demands an alternative selection technique (e.g., X-ray, IR) to optical emission-line diagnostics.

Much progress has been made in recent years based on these deep multi-wavelength surveys to determine the host galaxy properties of AGN (e.g., [12, 22]). In this review, I highlight our work using the COSMOS survey with specific attention on the zCOSMOS spectroscopic redshift survey and cospatial X-ray observations using XMM-Newton to identify the galaxies, based on their stellar mass and star formation rates, most likely to harbor an actively, accreting SMBH. We refer the reader to the full publication [16] that provide details on the methods and analysis techniques.

1.2 Star formation rates in zCOSMOS galaxies hosting AGN

We use the zCOSMOS 10k spectroscopic redshift catalog [23, 24] to investigate the properties of galaxies hosting AGN and their relation to the parent population. XMM-Newton observations [25, 26] of the full zCOSMOS sample enable us to identify 152 AGNs that include those with significant obscuration and of low optical luminosity. The derived properties such as host galaxy stellar mass, rest-frame color, and emission-line strength allow us to determine the prevalence of AGN activity as a function of these quantities. Specifically, we measure the SFR of galaxies using the [OII]λ3727 line luminosity [27]. We account for the contribution from the underlying AGN component most likely arising from the narrow-line region by using the observed [OIII]λ5007 luminosity and the typical [OII]/[OIII] ratio found from previous studies of type 1 AGN [28]. The [OIII] line luminosity is measured directly from our spectra if present. For the subsample with [OIII] outside our observed spectral bandpass, we infer the [OIII] strength from the hard (2–10 keV) X-ray luminosity and the well known correlation between these two quantities.

We find based on a stellar mass-selected sample of galaxies ($M_* > 4 \times 10^{10}$ $M_\odot$) that significant levels of star formation are present in the hosts of X-ray selected AGN (Figure 1.3). SFRs (1) range from $\sim 1 - 100$ $M_\odot$ yr^{-1}, with an average SFR higher than that of galaxies with equivalent stellar mass, and (2) evolve with cosmic time in a manner that closely mirrors the overall galaxy population. Such evolution appears to be consistent with the low SFRs in AGNs ($z < 0.35$) from the SDSS. Therefore, we find no evidence for significantly reduced levels of star formation in the hosts of AGNs and conclude that massive galaxies with plentiful gas supplies are most conducive for AGN activity. This analysis effectively extends the clear association of AGN activity and star formation, seen in low-redshift studies with the SDSS [19], up to $z \sim 1$. We note that similar findings are obtained here with additional spectral indicators, in particular $D_n(4000)$ and rest-

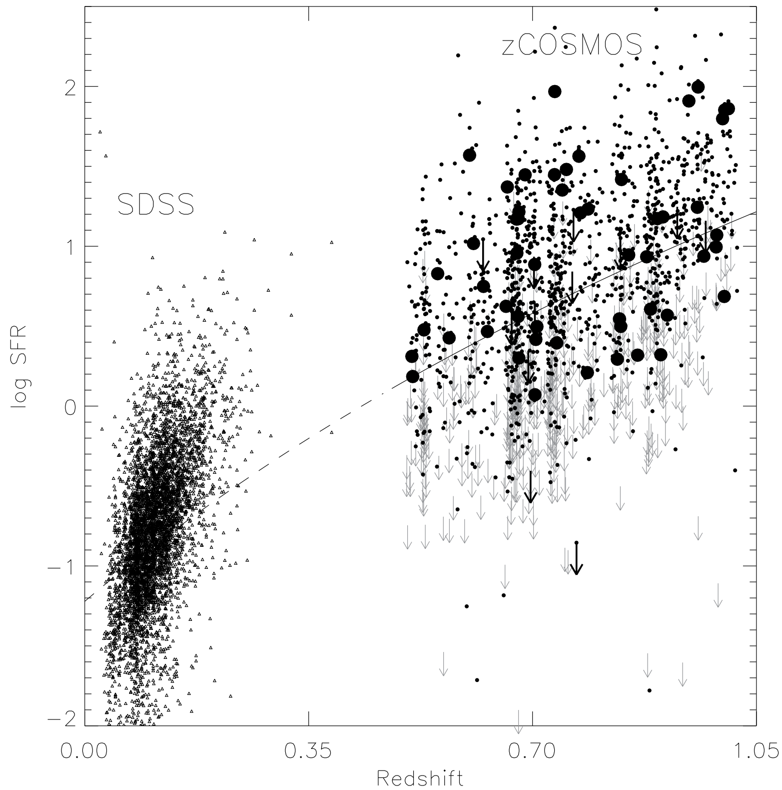

Fig. 1.3. Star formation rate versus redshift for zCOSMOS galaxies ($0.5 < z < 1.0$) with those hosting AGN marked by the large black circles. Upper limits are shown by the arrows. For comparison, type 2 AGNs from the SDSS are shown at $z < 0.35$ (small dots; [19]).

frame optical colors $U - V$ (see the following section). Finally, we highlight that these results are consistent with the color evolution of AGN hosts, seen in the *Chandra* Deep Field - South survey [13], that follow that of the underlying galaxy population (See Figure 1.2 *right* panel).

1.3 Further remarks on color-magnitude diagrams of AGN hosts

Much emphasis has been recently placed on the fact that AGN host galaxies have rest-frame optical colors between that of blue, star-forming galaxies and those of redder evolved galaxies (e.g., [12, 13, 15]). Such observations have been thought to lend support for the role of AGNs in quenching star formation. Although, a deficiency of AGNs within the blue galaxy population appears to be in disagreement with the SFRs of AGN hosts in zCOSMOS

galaxies presented above and also with the fact that local ULIRGS have not only high SFRs but enhanced levels of AGN activity [30].

With this in mind, we venture further to understand why the rest-frame colors of the hosts of AGN exhibit a difference in stellar age of about a gigayear from that of star-forming galaxies. It is suspected that the discrepancy arises due to mass selection since the hosts of type 2 AGNs in SDSS [19] do not exhibit such a difference with late-type galaxies of equivalent stellar mass. To check this, we simply determined the fraction of galaxies hosting X-ray selected AGN as a function of rest-frame color for both a luminosity and mass selected sample. As shown Figure 1.4, the difference between the two selection methods is in the fraction of blue ($U - V < 1.5$) galaxies hosting AGN. The mass selection mitigates the inclusion of galaxies having low mass-to-light ratios that mainly pertains to those forming stars. Since the incidence of AGN activity is known to rise with the stellar mass of its host galaxy (See Figure 7 of [16]), the decline in AGN fraction from the 'green valley' to the 'blue cloud' seen in luminosity limited samples is driven by the preponderance of low mass galaxies that are not likely to harbor AGN of these X-ray luminosities. **Simply put, the dependence of AGN activity on stellar mass must be taken into consideration before making claims regarding the color dependency of AGN activity in luminosity-selected samples.** In light of this check for consistency, we conclusively find that not only our SFRs based on [OII] but the rest-frame colors $U - V$ and spectral index $D_n(4000)$ all indicate that AGN prefer to reside in galaxies with substantial levels of star formation in agreement with related studies at similar redshifts [31, 32, 33].

1.4 Conclusion: co-evolution of SMBHs and their host galaxies

We have demonstrated that star formation with rates between $\sim 1 - 100$ $M_\odot$ yr^{-1} is present in the hosts of AGN up to $z \sim 1$. The question now is how closely does star formation track the mass accretion rate onto these SMBHs? To answer this question, we have converted the X-ray luminosity to a mass accretion rate assuming a bolometric correction and accretion efficiency. In Figure 1.5, we plot the relative growth rate of these SMBHs to their host galaxies (dM_{accr} dt^{-1} / SFR). We find that a significant amount of dispersion is present thus indicating that a direct relationship between star formation and black hole accretion does not occur on a case-by-case basis (See Figure 13a of [16]). On average, a co-evolution scenario is clearly evident given the constancy of this ratio ($\sim 10^{-2}$) with redshift. Remarkably, this ratio is in very good agreement with that of low redshift type 2 AGNs

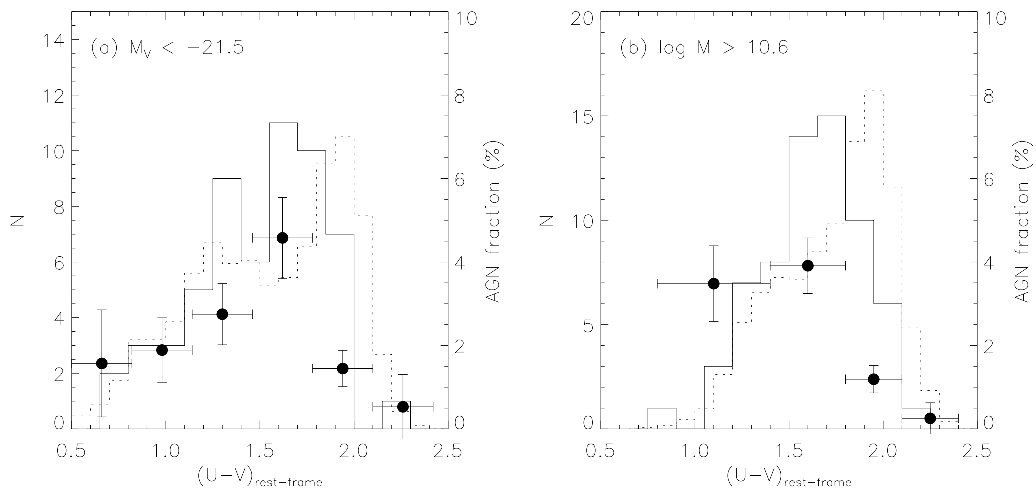

Fig. 1.4. Rest-frame color distribution of zCOSMOS galaxies (dashed histogram) and those hosting AGN (solid histogram) for luminosity (left panel) and mass (right panel) selected samples. Data points show the fraction of galaxies hosting AGN with $L_{0.5-8\mathrm{keV}} \sim 10^{43}$ erg s^{-1}.

in SDSS [34]. The order-of-magnitude increase in this ratio compared to the locally measured value of M_{BH}/M_{bulge}, is consistent with an AGN lifetime substantially shorter than that of star formation. This mutual decline in global star formation and accretion onto SMBHs, as introduced in Figure 1.1, is now evident within galaxies hosting AGN themselves effectively shifting such a co-evolution scenario to smaller physical scales.

Overall, we conclude that the properties of these X-ray selected AGN and their host galaxies are not in accord with merger-driven models [5] of SMBH accretion with feedback. Even though their SFRs are quite high, their structural properties are not indicative of being predominantly associated with such disturbed systems (e.g., [22]). Although, their hosts are massive and bulge-dominated thus suggesting that a merger event must have happened although prior (> 1 Gyr) to the AGN phase. As presented above, the impact of AGNs on their hosts may be minimal, based on the levels of star formation, thus bringing into question the efficiency of AGN feedback implemented in current semi-analytic models. Given the moderate-luminosities of these X-ray selected AGNs ($L_X \sim 10^{43}$ erg s^{-1}), a "Seyfert mode" of accretion driven by secular processes [35] is more likely for this class of accreting SMBHs while the more luminous QSOs [36, 37] may provide the missing link to a merger-induced accretion mode.

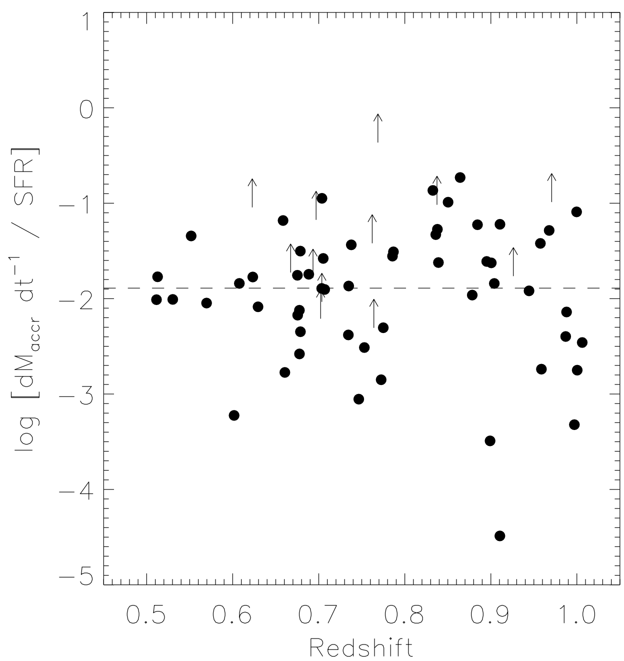

Fig. 1.5. Ratio of SMBH accretion to SFR versus redshift. The horizontal dashed line marks the median ratio. Measurements are shown by a solid circle while lower limits lower are given by an arrow.

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